# Direct Photon Emission from Heavy Ion Collisions

**Axel Drees, Stony Brook University**

**GHP**2017

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- **Introduction**

- **Previous Results form PHENIX**
  - **High low $p_T$ direct photon yield**
  - **Centrality dependence ~ $N_{part}^{1.4}$**
  - **Large direct photon angular anisotropy $v_2$ and $v_3$**

- **Comparison to Theoretical Models**
  - **Thermal Photon Puzzle**

- **New Direct Photon Measurements**
  - **Cu+Cu at 200 GeV**
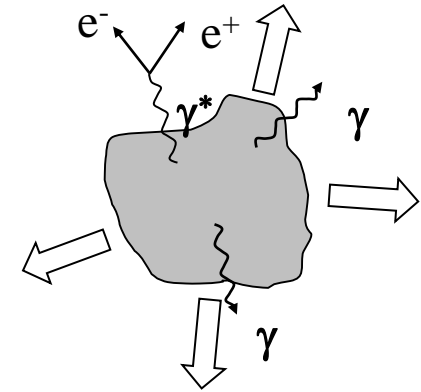  - **Au+Au at 62.4 and 39 GeV**

- **Outlook and Summary**

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# Thermal Radiation from Hot & Dense Matter

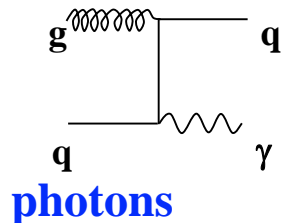● **Black Body Radiation**

   ○ **Real or virtual photons**

   ○ **Spectrum and yield sensitive to temperature**
      **Avg. inv. slope $\propto T$, Rate $\propto T^4$**

   ○ **Space-time evolution of matter**
      **collective motion → Doppler shift**
      **→ anisotropy**
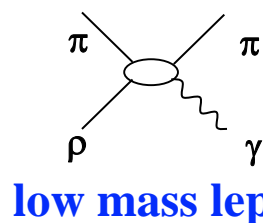


**High yield → high T → early emission**
**Large Doppler shift → late emission**

● **Microscopic view of thermal radiation**
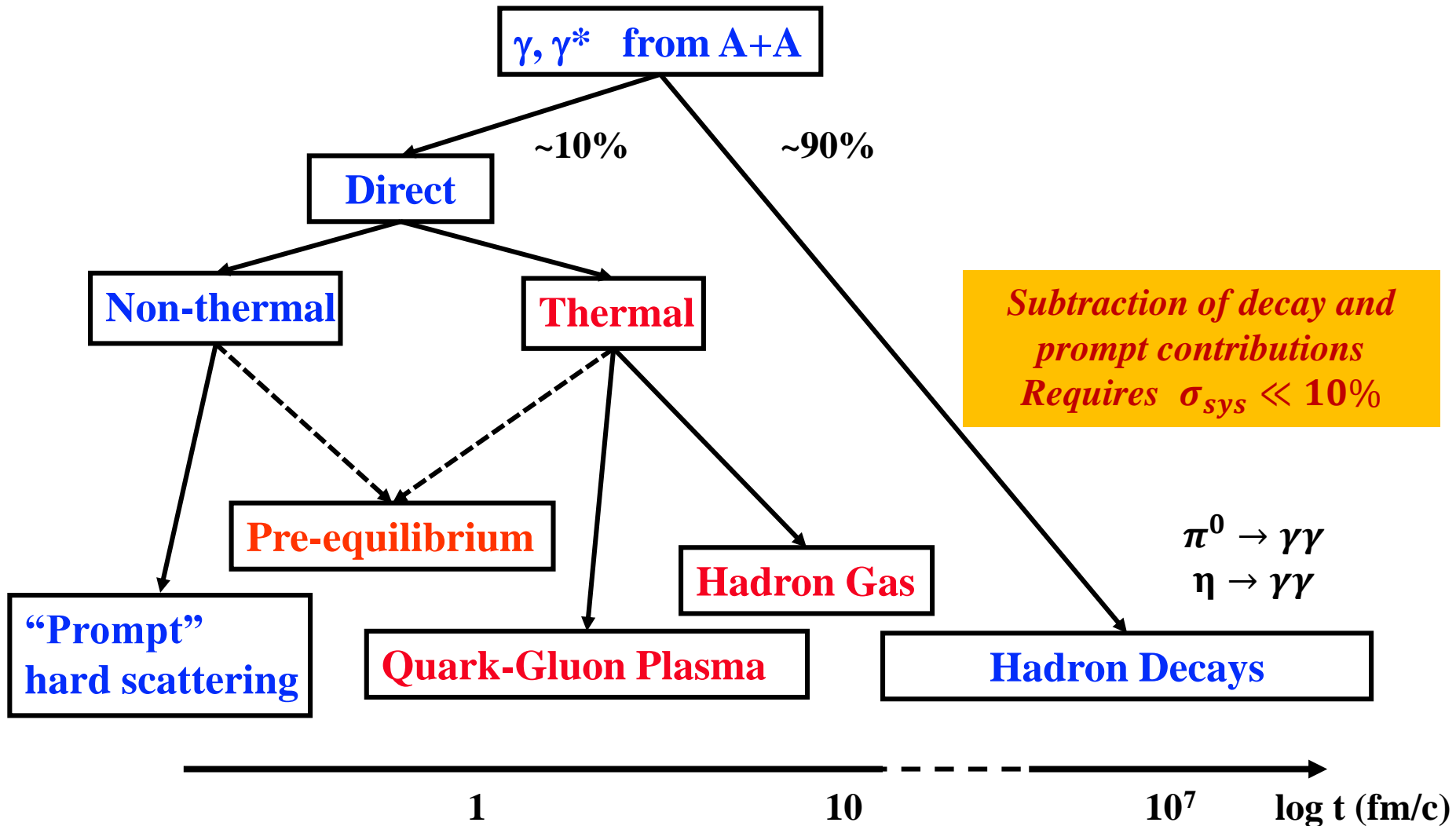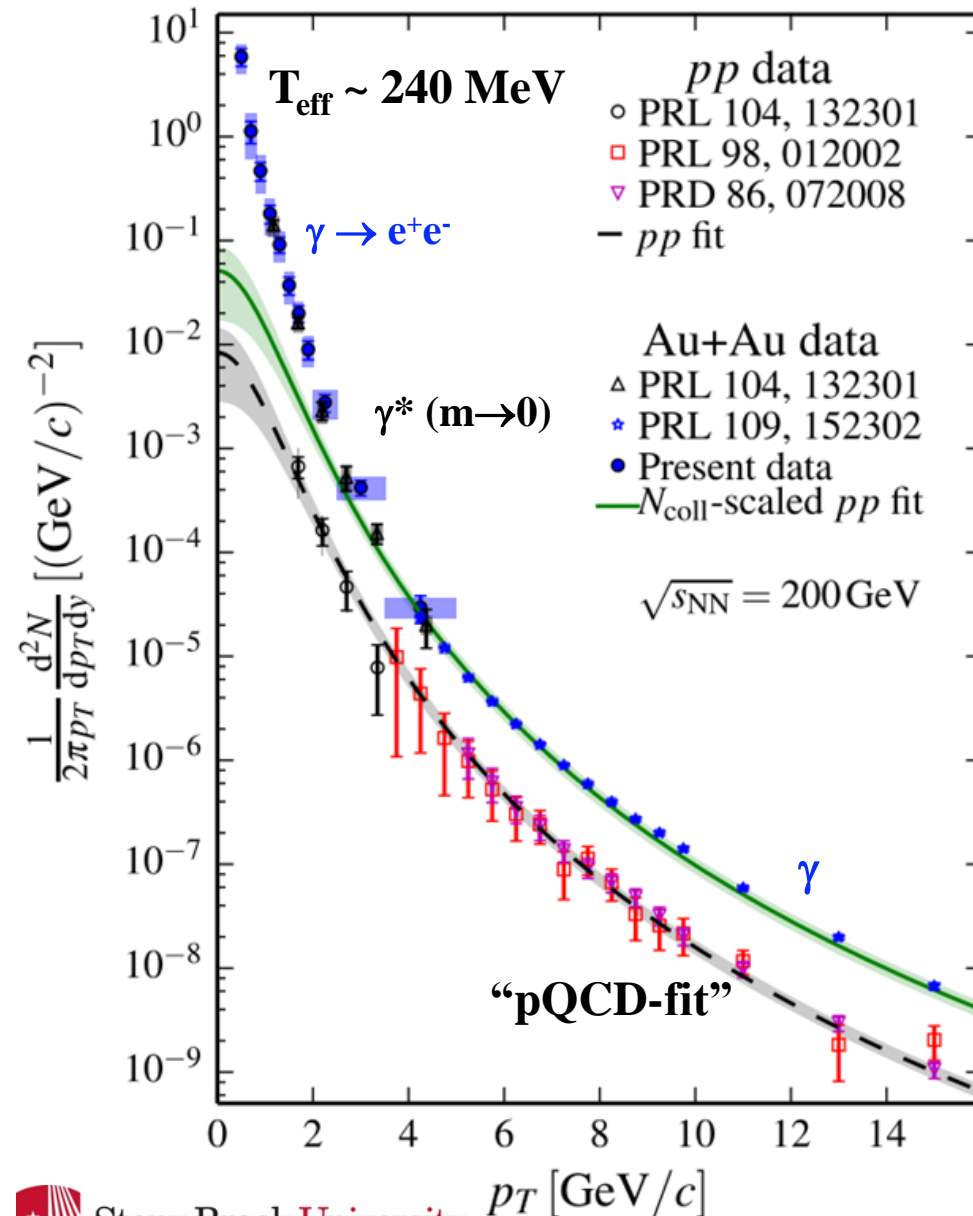
**QGP:**　　　　　　**hadron gas:**



**photons**　　　**low mass lepton pairs**

**Data constrain initial conditions, emission rates and space-time evolution**

# Experimental Issue: Isolate Thermal Radiation



$\gamma, \gamma^*$ from A+A

~10%     ~90%

**Direct**

**Non-thermal**     **Thermal**

**Subtraction of decay and prompt contributions Requires $\sigma_{sys} \ll 10\%$**

**Pre-equilibrium**

**Hadron Gas**

$\pi^0 \to \gamma\gamma$
$\eta \to \gamma\gamma$

**"Prompt" hard scattering**

**Quark-Gluon Plasma**

**Hadron Decays**

1     10     $10^7$     log t (fm/c)

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# Direct Photons p+p and Au+Au at √s_NN 200GeV

$\sqrt{s}_{NN}$ 200GeV



*PHENIX: Phys. Rev. C 91 064904 (2015)*

Plot legend:
- $T_{eff} \sim 240$ MeV
- $\gamma \rightarrow e^+e^-$
- $\gamma^* (m \rightarrow 0)$

pp data
- ○ PRL 104, 132301
- □ PRL 98, 012002
- ▽ PRD 86, 072008
- — pp fit

Au+Au data
- △ PRL 104, 132301
- ★ PRL 109, 152302
- ● Present data
- — $N_{coll}$-scaled pp fit

$\sqrt{s_{NN}} = 200\,\text{GeV}$

"pQCD-fit"

$\gamma$

y-axis: $\dfrac{1}{2\pi p_T}\dfrac{d^2N}{dp_T dy}\left[(\text{GeV}/c)^{-2}\right]$

x-axis: $p_T$ [GeV/c]

- **Direct photon yield well established**
  - **pp consistent with pQCD**
  - **AuAu follows $N_{coll}$ scaled pp above 4 GeV**
  - **Significant excess below 3 GeV in AuAu**
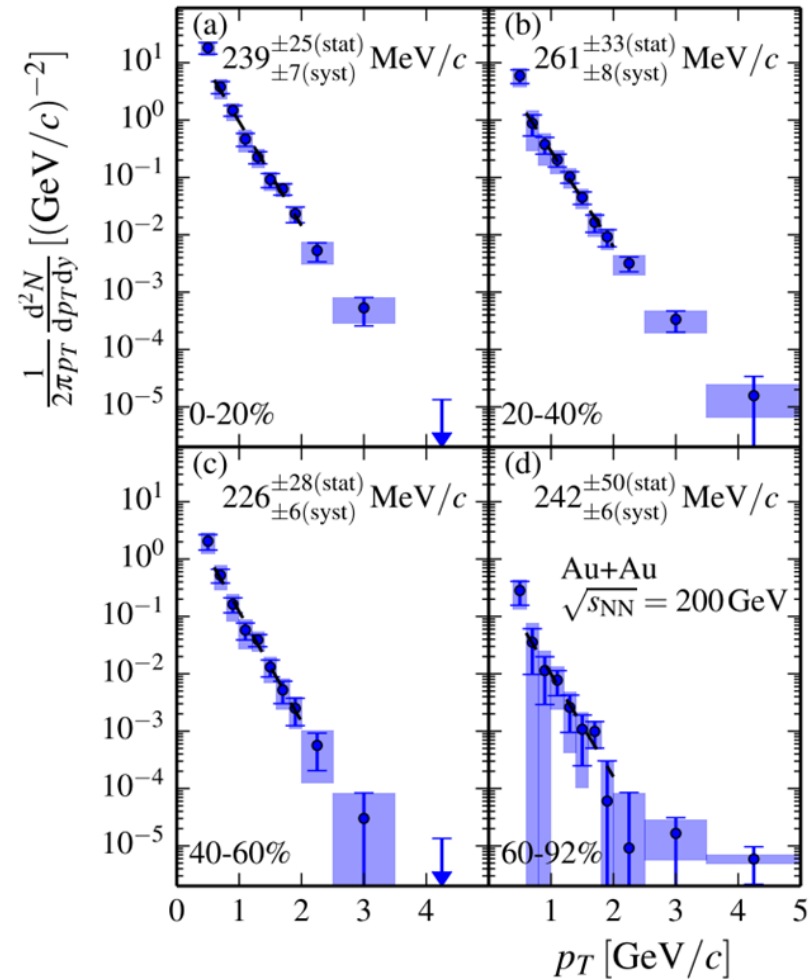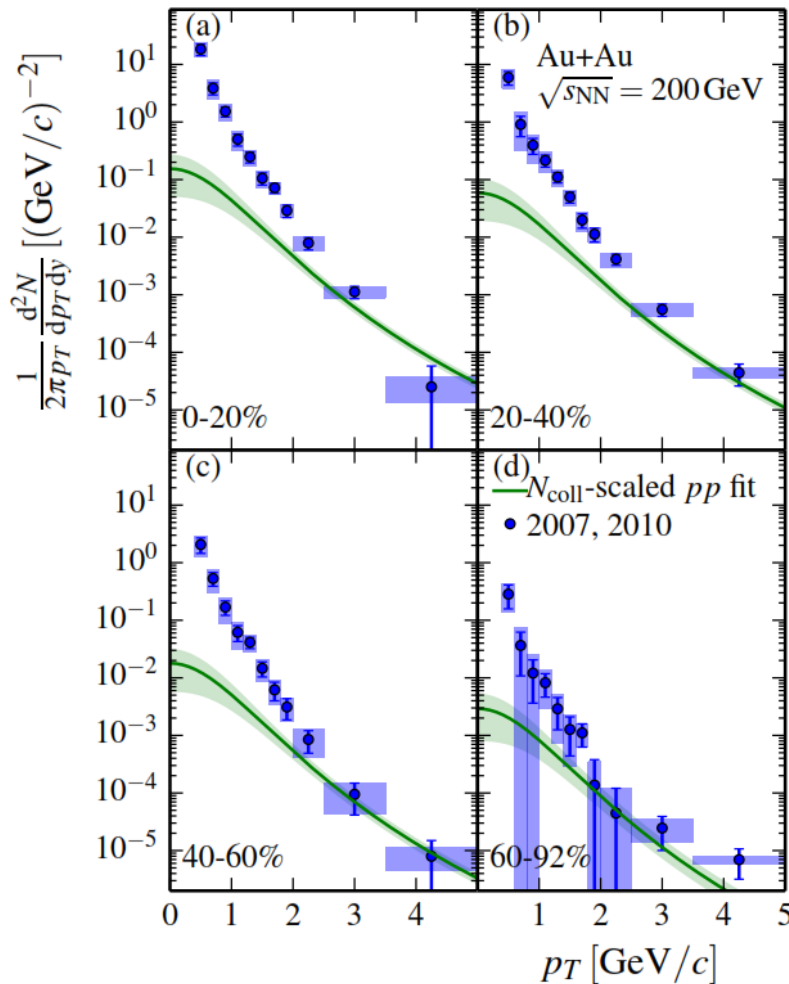  - **Excess has nearly exponential shape**

**large photon yield:**
**$T_{ini} > 240$ MeV $> T_C$**

**yield $\propto N_{part}^{1.38 \pm 0.3 \pm 0.07}$**

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# Centrality Dependence of Thermal Component

**Large direct photon excess**
**yield** $\propto N_{part}^{1.38\pm0.3\pm0.07}$ **with inv. slope T ~ 240 MeV**

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# Anisotropic Emission of Direct Photons
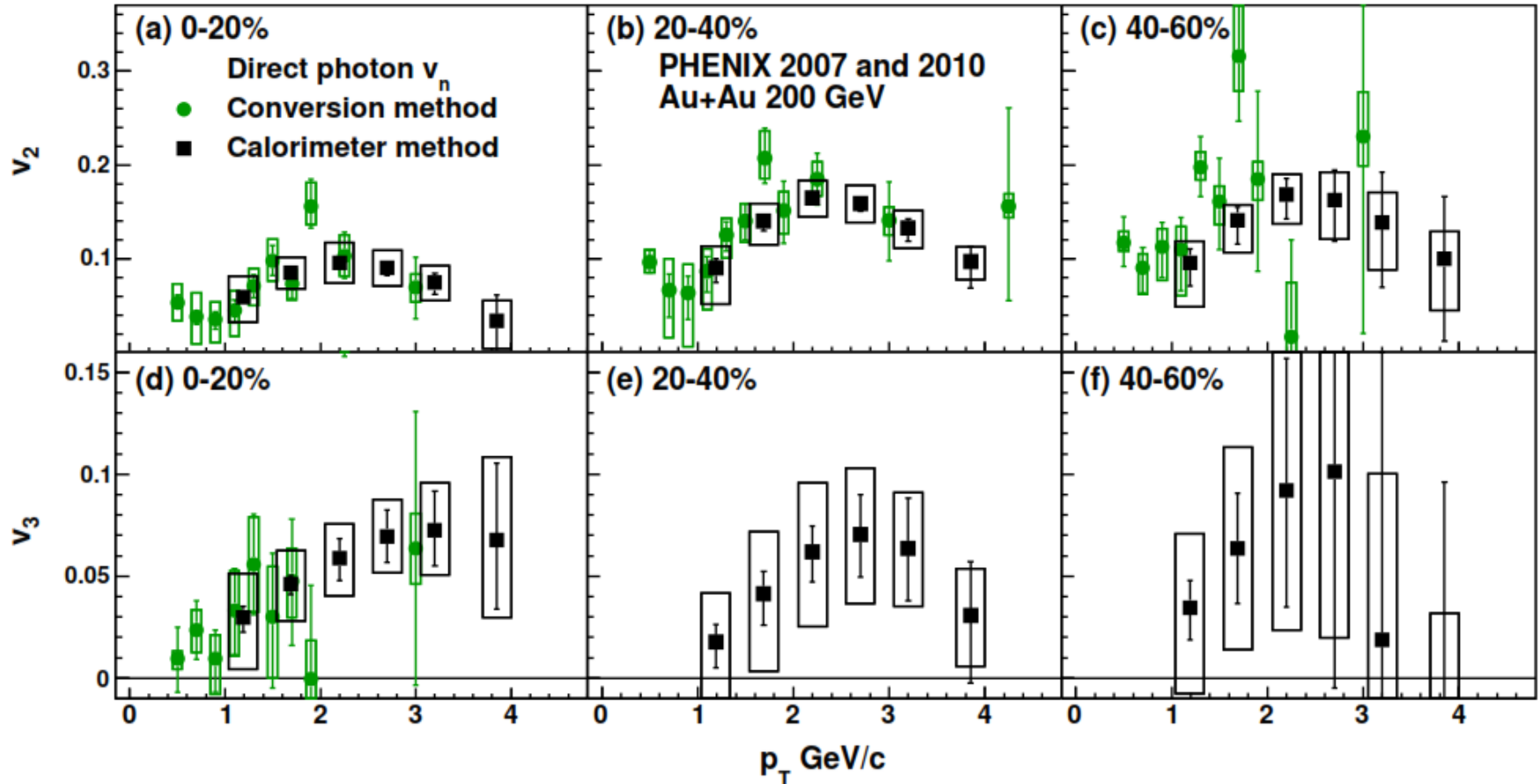
**Anisotropic emission of direct photon with large $v_2$ and $v_3$**

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# Direct Photon Puzzle

**Many model calculations and consideration\*:**

- **More traditional, large contribution from hadron gas**
  - **Thermal rate in QGP & HG, with hydro (viscous/non viscous) or blastwave evolution**
  - **Microscopic transport (PHSD)**

- **New early contributions**
  - **Non-equilibrium effects (glasma, etc.)**
  - **Enhanced thermal emission in large B-fields**
  - **Modified formation time and initial conditions**

- **New effects at phase boundary**
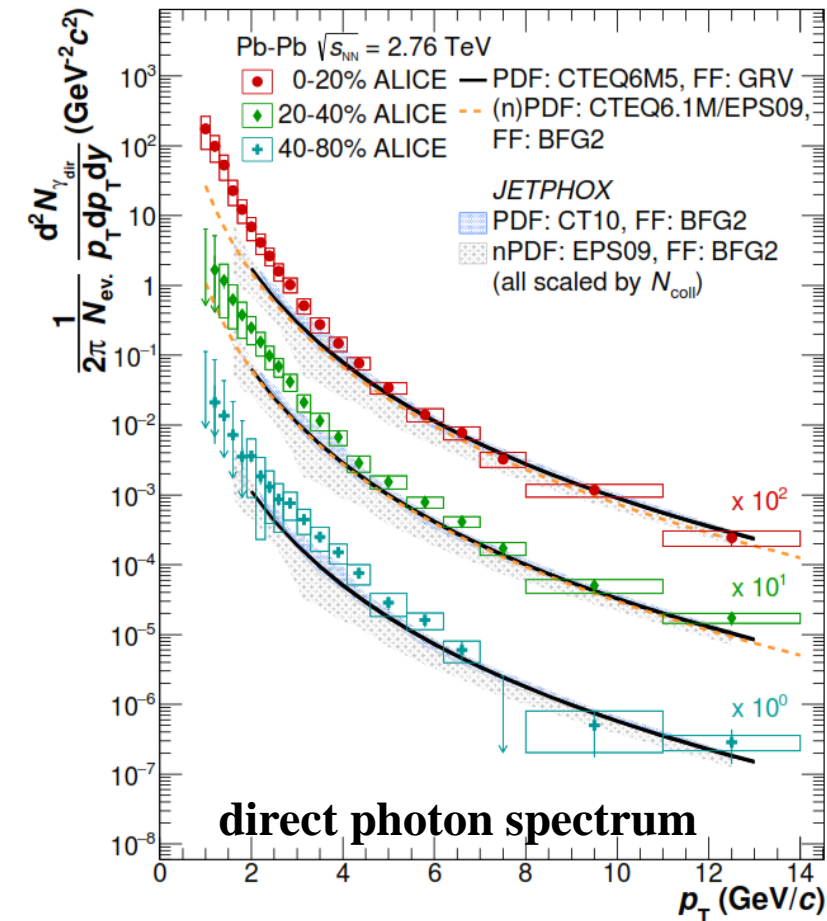  - **Extended emission**
  - **Emission at hadronization**

*\*list not complete*



(a) Invariant yield

- Fireball senario
- Semi-QGP w/o viscous
- PHSD
- Initial strong magnetic field

$E\frac{d^3N}{dp^3}$ (GeV$^2$)

Au+Au 20-40%
$\sqrt{s_{NN}}$=200GeV

Yield is from PRC 91, 064904

$p_T$ (GeV/c)

(b) $v_2$

(c) $v_3$   PHENIX

- Calorimeter
- Conversion

$p_T$ (GeV/c)
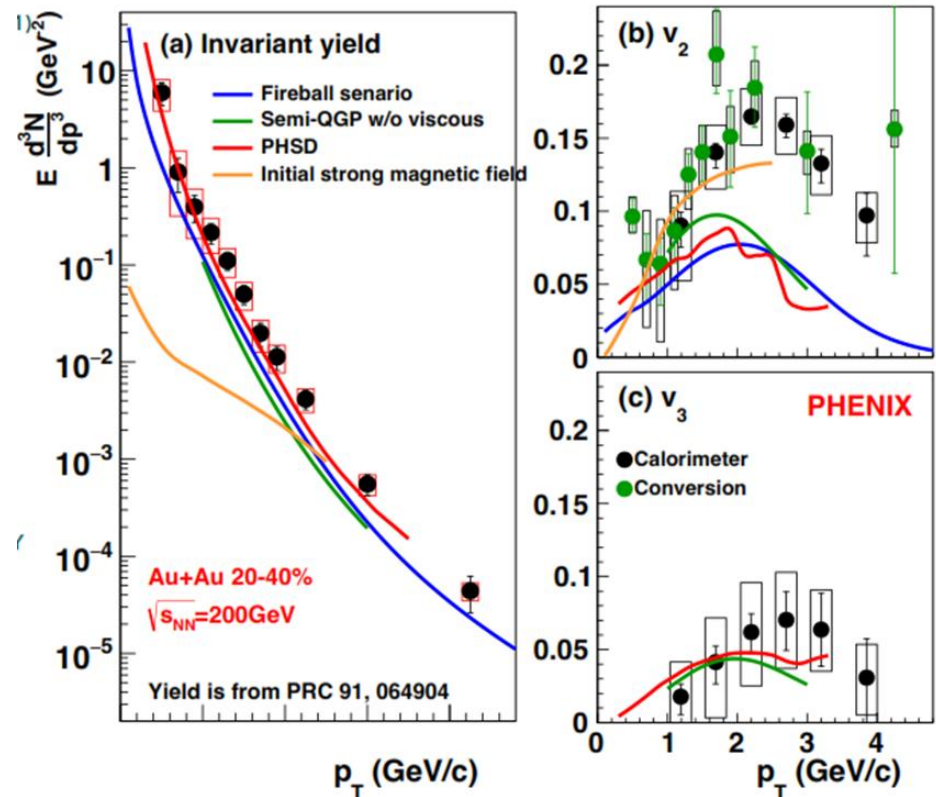
**Large yield and $v_n$ challenge understanding of sources, emission rates and space-time evolution**

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# First Results from LHC

Central Pb+Pb 2.76 TeV:

$$T_{eff}^{no\,subtr} = (304 \pm 11^{stat} \pm 40^{syst})\,MeV$$



**direct photon spectrum**
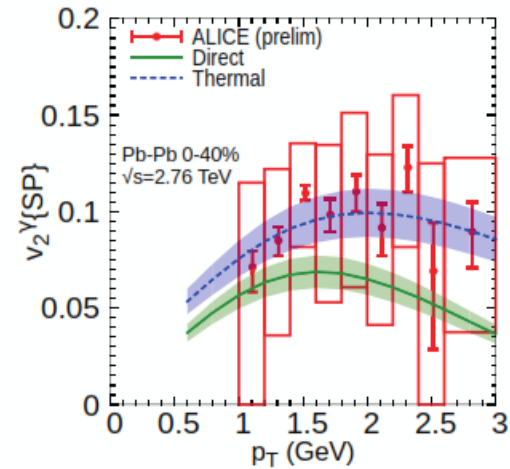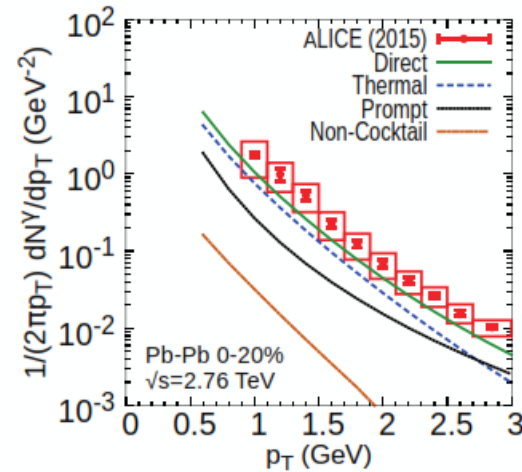
**Direct photon flow and yield at LHC:
Similar trend as PHENIX, within large $\sigma_{sys}$**

# Photon Measurements with PHENIX

**e⁺e⁻ identification**

**E/p and RICH**

**Photons, neutral pion**

$\gamma, \pi^0 \to \gamma\,\gamma$

**Calorimeter**

PC3
Central
Magnet
PC2
PbSc
TEC
PC3
PbSc

DC

**DC**

TOF
PbSc
RICH
DC
DC
RICH
PbGl

$e^+$
$\gamma^*$
$\gamma$

$e^-$
$\gamma$

MPC
HBD
RxNP

**PC1**
PC1
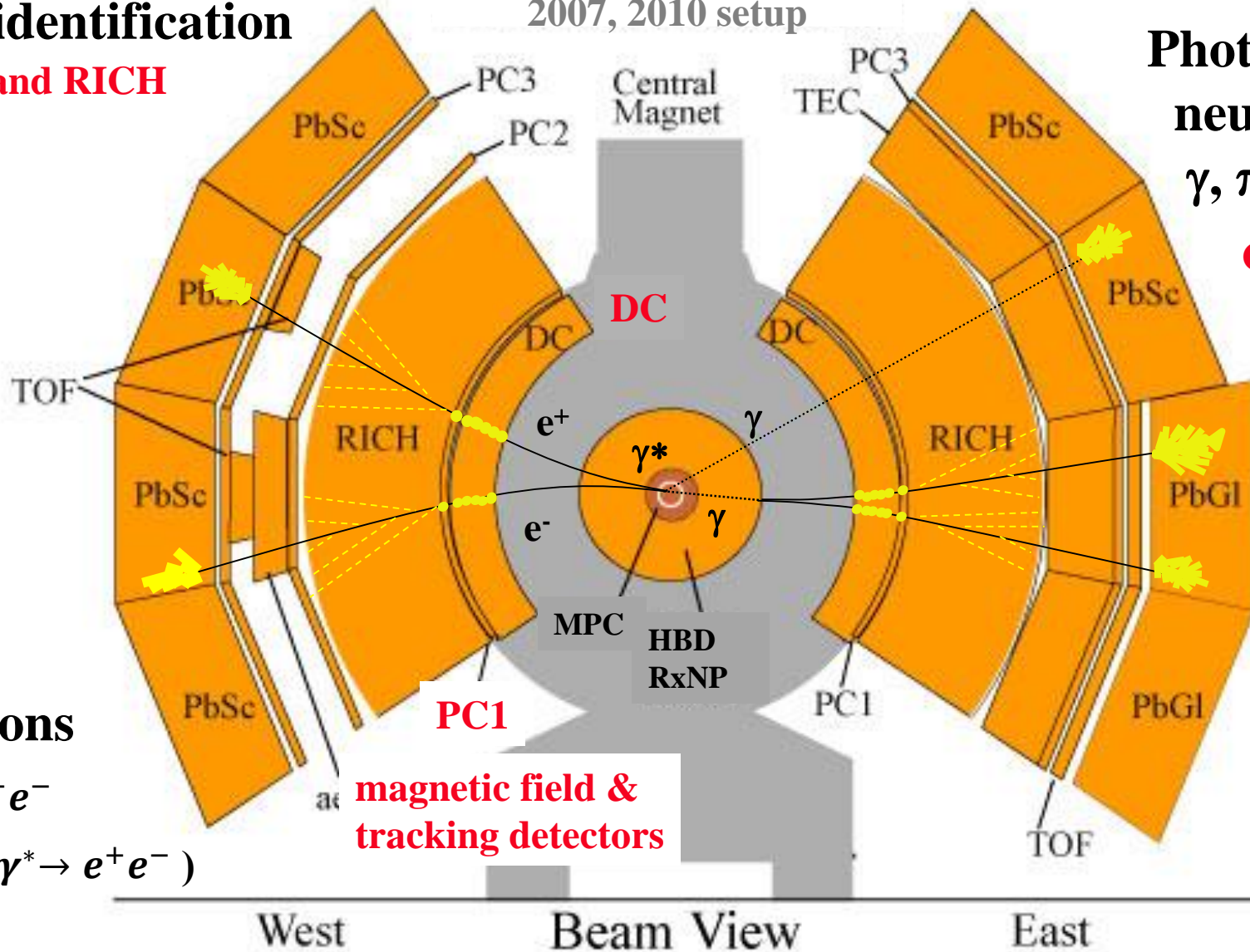
**magnetic field & tracking detectors**

PbSc
PbGl

TOF

**Photons**

$\gamma \to e^+ e^-$

$$\lim_{m_{ee} \to 0} (\gamma^* \to e^+ e^-)$$

West          Beam View          East

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# Using $\gamma^*$ to Measure Direct Photons

- **Searches for thermal photons ongoing since late 1980's at SPS**
  - **WA80 & successors, HELIOS, CERES …**
  - **Established mostly upper limits in relevant range $p_T <$ few GeV**

- **Breakthrough at PHENIX: Measuring direct photons via virtual photons – published 2010**  *PHENIX Phys.Rev.Lett 104 (2010) 132301*
  - **Method originally proposed by UA1 for prompt photons**

- **Using virtual photons $\gamma^*$:**
  - **any process that radiates $\gamma$ will also radiate $\gamma^*$**
  - **for $m \ll p_T$ $\gamma^*$ are "almost real"**
  - **extrapolate $\gamma^* \to e^+e^-$ yield to $m = 0$ → direct $\gamma$ yield**
  - **$m > m_\pi$ cut removes 90% of hadron decay background**
  - **S/B improves by factor 10 so that 10% direct $\gamma$ → 100% direct $\gamma^*$**
  - **measure ratio $\gamma^*_{direct}/\gamma^*_{inclusive}$ for sys. uncertainty cancelation**

# Fit e⁺e⁻ Mass Distribution to Extract the Direct Yield:
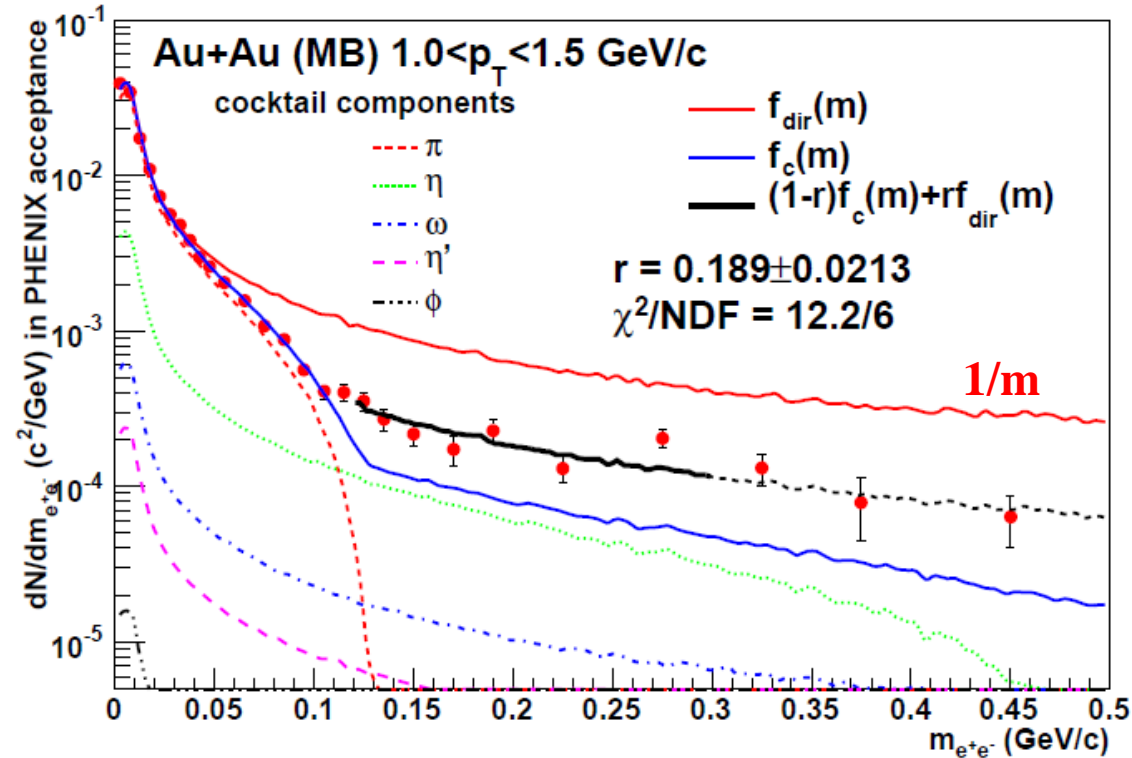
- **Example: one $p_T$ bin for Au+Au collisions**

$$\frac{d\sigma_{ee}}{dM^2 dp_T^2 dy} \cong \frac{\alpha}{3\pi} \frac{1}{M^2} L(M) \frac{d\sigma_{\gamma}}{dp_T^2 dy}$$

$f_c(m_{ee})$ and $f_{dir}(m_{ee})$

normalized to data

for $m_{ee} < 30\, MeV$

$$r = \frac{\gamma_{dir}^*}{\gamma_{incl}^*} = \frac{\gamma_{dir}}{\gamma_{incl}}$$



Au+Au (MB) 1.0<$p_T$<1.5 GeV/c

cocktail components

- - - π
- - - η
- - - ω
- - - η'
- - - φ

—— $f_{dir}(m)$
—— $f_c(m)$
—— $(1-r)f_c(m)+rf_{dir}(m)$

r = 0.189±0.0213
$\chi^2$/NDF = 12.2/6

**1/m**

Direct γ* yield fitted in range 120 to 300 MeV
Insensitive to $\pi^0$ yield

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# Fit e⁺e⁻ Mass Distribution to Extract the Direct Yield:

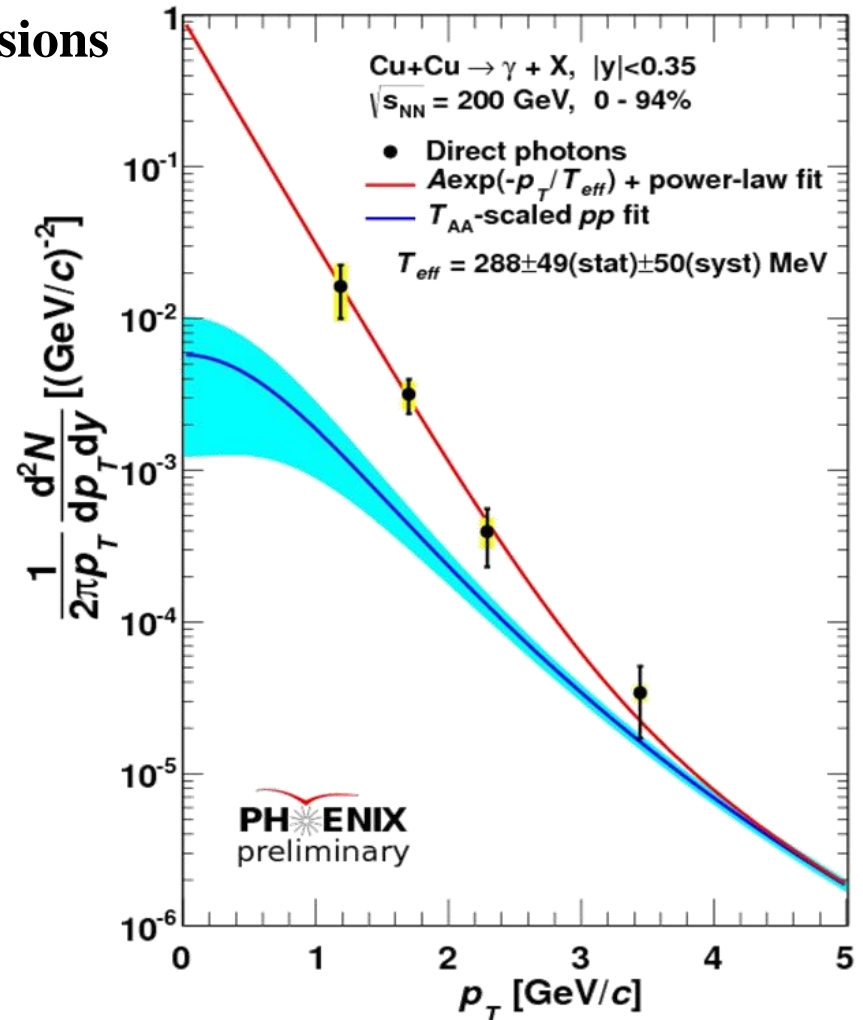- **Example: one $p_T$ bin for Au+Au collisions**

$$\frac{d\sigma_{ee}}{dM^2 dp_T^2 dy} \cong \frac{\alpha}{3\pi} \frac{1}{M^2} L(M) \frac{d\sigma_\gamma}{dp_T^2 dy}$$

$f_c(m_{ee})$ and $f_{dir}(m_{ee})$

normalized to data

for $m_{ee} < 30\,MeV$

$$r = \frac{\gamma_{dir}^*}{\gamma_{incl}^*} = \frac{\gamma_{dir}}{\gamma_{incl}}$$



Cu+Cu → γ + X, |y|<0.35
$\sqrt{s_{NN}}$ = 200 GeV, 0 - 94%

- Direct photons
— $A\exp(-p_T/T_{eff})$ + power-law fit
— $T_{AA}$-scaled $pp$ fit

$T_{eff}$ = 288±49(stat)±50(syst) MeV

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preliminary

**Clear direct photon signal in Cu+Cu data at $\sqrt{s_{NN}}$ = 200 GeV !
Inverse slopes consistent within large uncertainty with Au+Au**

# Direct Photons from Photon Conversions

🔴 **Double ratio tagging method** *(PHENIX: Phys. Rev. C 91 064904 (2015))*

- **Clean photon sample with photon conversion in detector material (HBD)**

$$\gamma \to e^+ e^-$$

- **Explicit cancelation of systematic uncertainties**
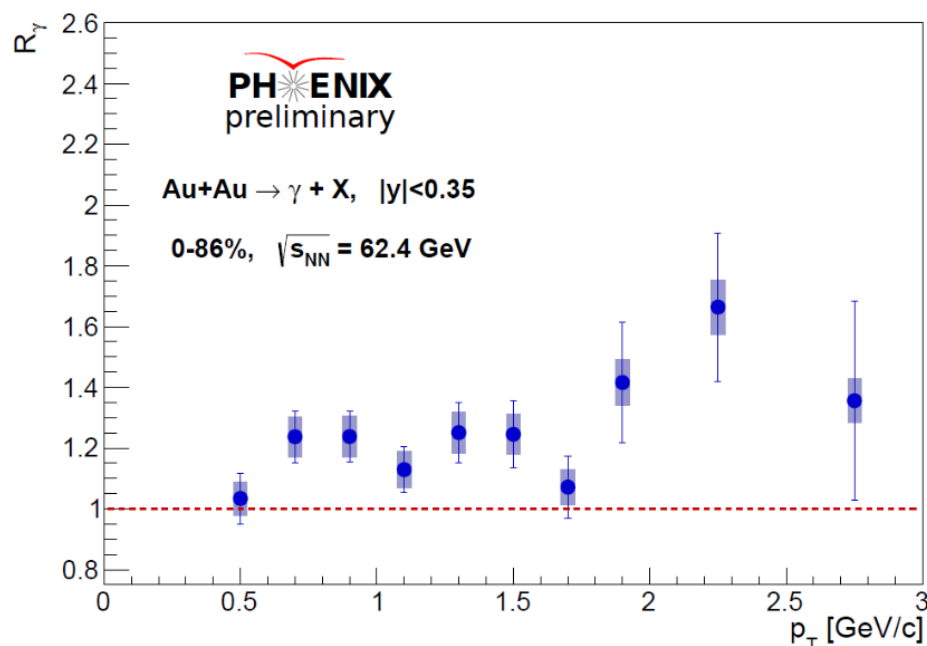- **Data taken in 2010 together with published 200 GeV data**

$$\frac{Y_\gamma^{incl}}{Y_\gamma^{\pi^0 tag}} = \frac{N_\gamma^{incl}}{N_\gamma^{\pi^0 tag}} \frac{p_{conv} a_{ee} \varepsilon_{ee}}{p_{conv} a_{ee} \varepsilon_{ee} \langle \varepsilon f \rangle} = \frac{N_\gamma^{incl}}{N_\gamma^{\pi^0 tag} \langle \varepsilon f \rangle}$$

| conditional tagging efficiency | measured raw yields |
|---|---|

$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{hadr}} = \frac{\langle \varepsilon f \rangle \times \left( \dfrac{Y_\gamma^{incl}}{Y_\gamma^{\pi^0 tag}} \right)^{Data}}{\left( \dfrac{N_\gamma^{hadr}}{N_\gamma^{\pi^0}} \right)^{MC}}$$
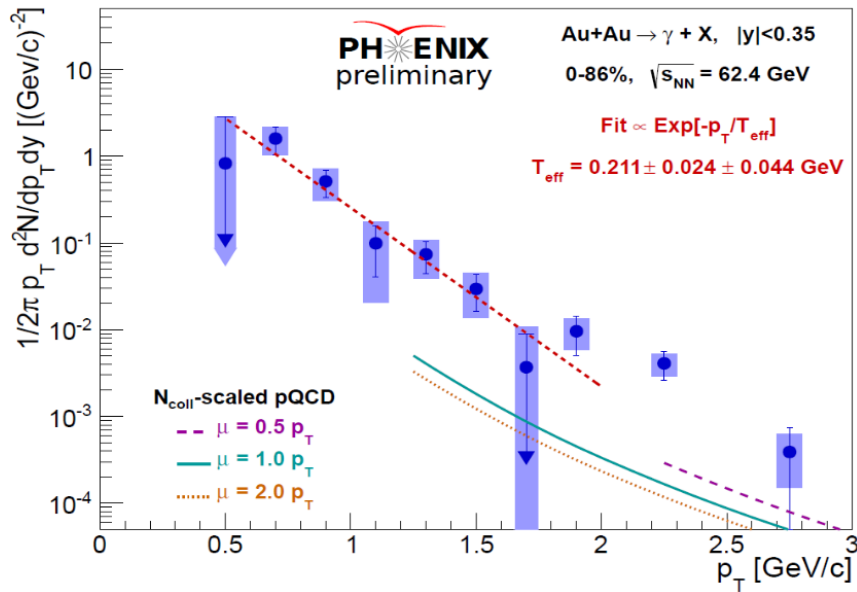
**simulated based On hadron data**

$$\text{note on vritual photon } r_\gamma = \frac{\gamma_{dir}}{\gamma_{incl}} \rightarrow 1 - r_\gamma = \frac{1}{R_\gamma}$$



$R_\gamma$

PHENIX preliminary

Au+Au $\to \gamma$ + X,   |y|<0.35

0-86%,  $\sqrt{s_{NN}}$ = 62.4 GeV

$p_T$ [GeV/c]

**New Au+Au data at 62.4 and 39 GeV!**

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# Au+Au Data at 62.4 GeV and 39 GeV

**min. bias Au+Au 62.4 GeV**



**min. bias Au+Au 39 GeV**



$T_{eff} = 0.211 \pm 0.024 \pm 0.044$ GeV
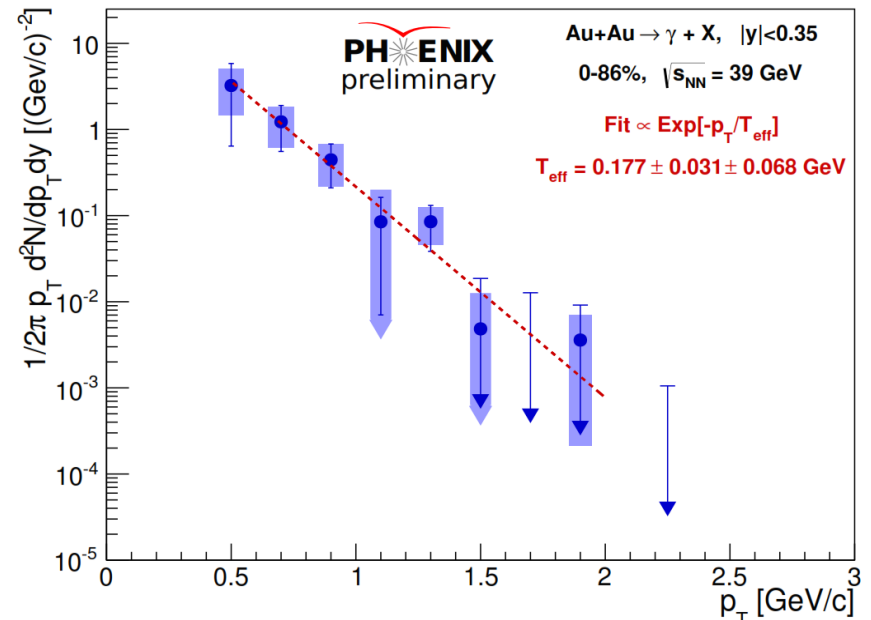
$T_{eff} = 0.177 \pm 0.031 \pm 0.068$ GeV

**Clear direct photon signal in Au+Au at 62.4 GeV and 39 GeV**

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# $T_{eff}$ vs Collision Energy
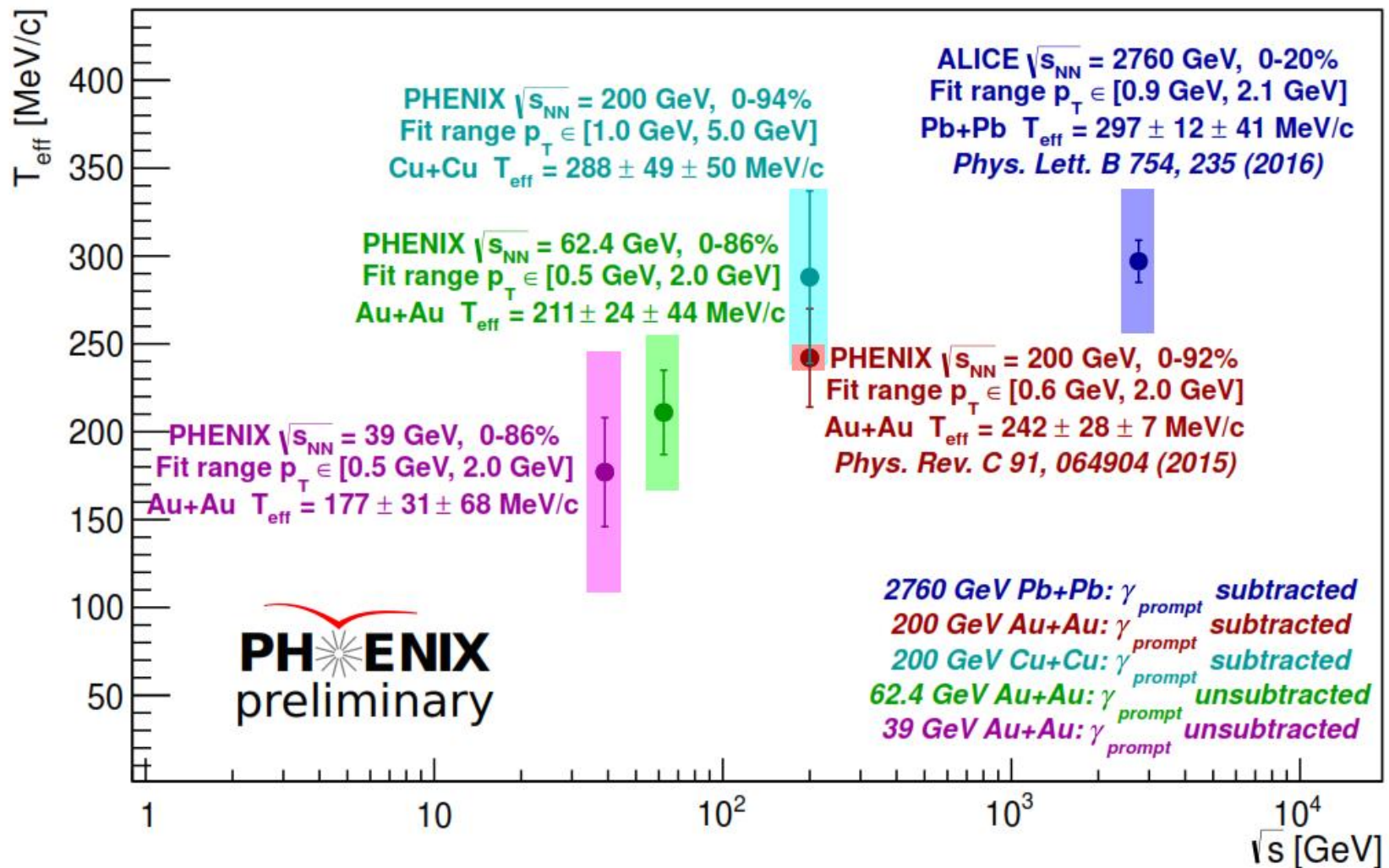


**Possible increase of $T_{eff}$ with increasing beam energy**

# Direct Photon Yield vs $N_{part}$
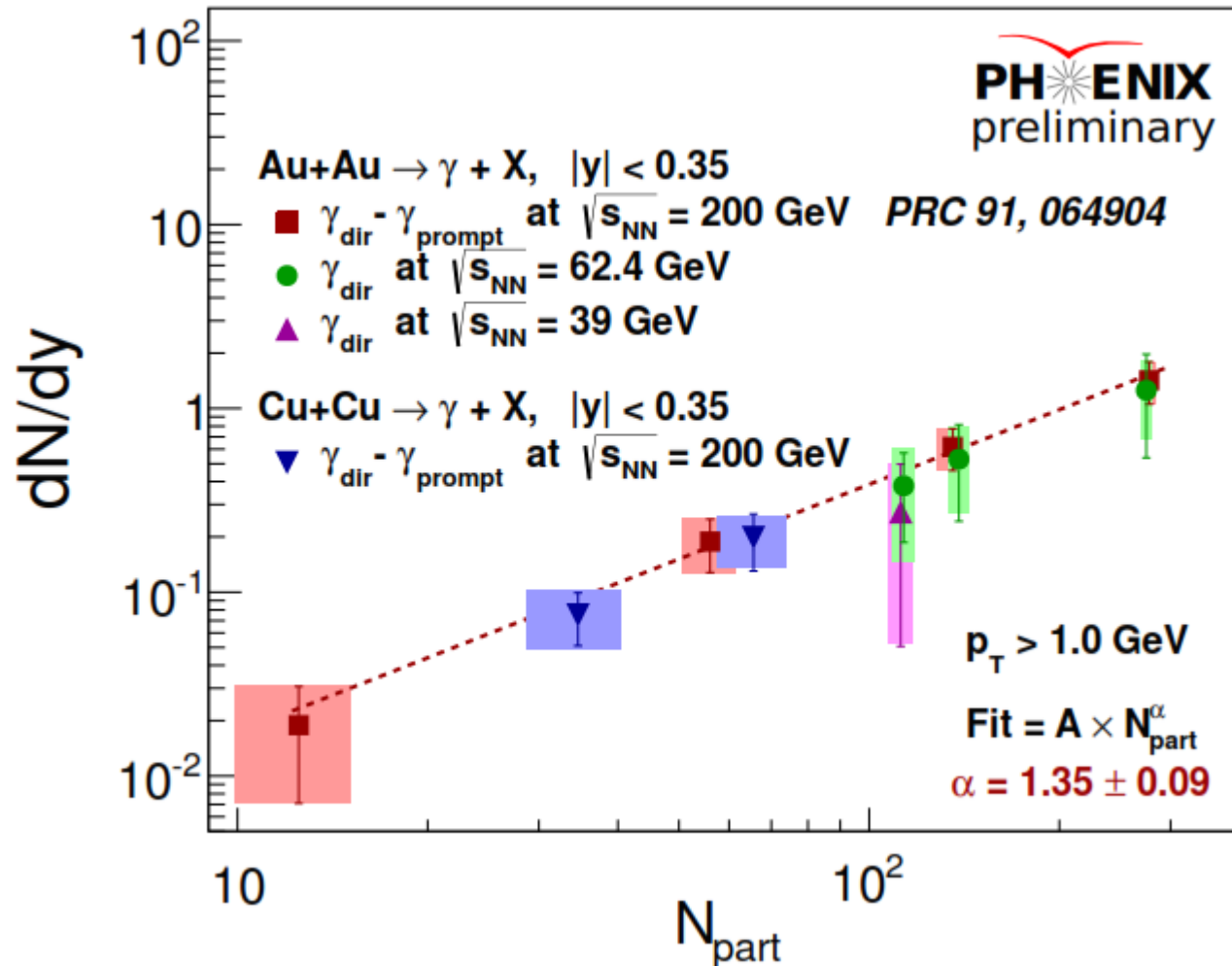


**yield** $\propto N_{part}^{\alpha}$
**with** $\alpha \sim 1.4$

$N_{part} \propto$ **volume**

Text within figure:

**PH✳ENIX preliminary**

Au+Au → $\gamma$ + X, |y| < 0.35
- $\gamma_{dir}$ - $\gamma_{prompt}$ at $\sqrt{s_{NN}}$ = 200 GeV   *PRC 91, 064904*
- $\gamma_{dir}$ at $\sqrt{s_{NN}}$ = 62.4 GeV
- $\gamma_{dir}$ at $\sqrt{s_{NN}}$ = 39 GeV

Cu+Cu → $\gamma$ + X, |y| < 0.35
- $\gamma_{dir}$ - $\gamma_{prompt}$ at $\sqrt{s_{NN}}$ = 200 GeV

$p_T$ > 1.0 GeV

Fit = A × $N_{part}^{\alpha}$
$\alpha$ = 1.35 ± 0.09

Y-axis: dN/dy
X-axis: $N_{part}$

**Similar increase with $N_{part}$ for different systems
Yield increases faster than reaction volume**

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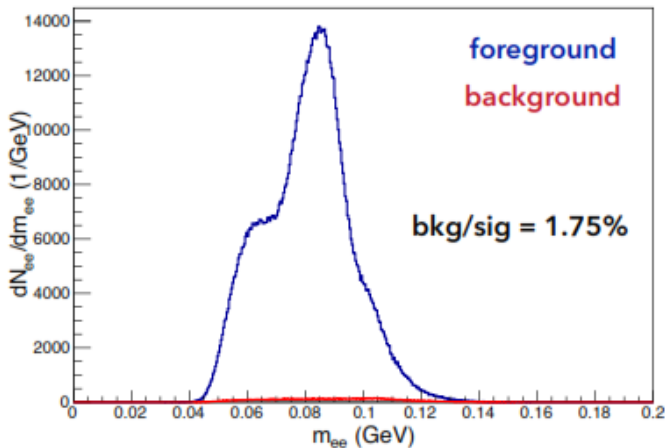
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# New γ→e⁺e⁻ Reconstruction Technique

Identify and reconstruct photons via external conversion to e⁺e⁻ pairs

- Previous method used single e⁺/e⁻ tracks (2010)
  - Conversions at fixed radius (Hadron Blind Detector readout plane at 60cm, ~3%)
- New method used e⁺e⁻ pairs (>2011)
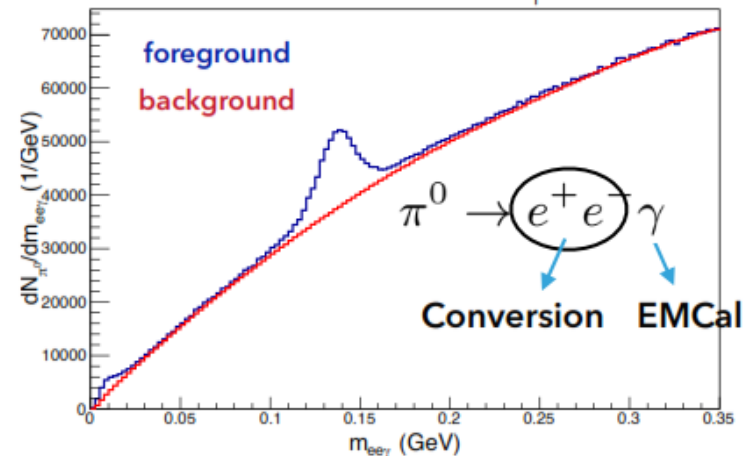  - Conversions at any material (VTX 3rd and 4th layer, ~10%)



mass distribution of different conversion radius

**MC simulation**
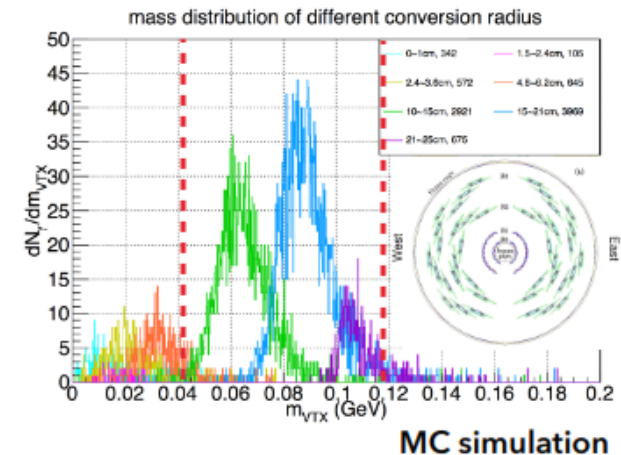
inclusive photon (e⁺e⁻) mass

Run14 AuAu @ 200 GeV, Min Bias, $p_T^{ee}$ 1.2~1.4GeV



foreground
background

bkg/sig = 1.75%

$\pi^0$ (e⁺e⁻γ) mass

Run14 AuAu @ 200 GeV, Min Bias, $p_T^{ee}$ 1.2~1.4GeV



foreground
background

$\pi^0 \rightarrow e^+e^- \gamma$

Conversion    EMCal

- Other systems: AuAu, CuAu, He3Au, pp, pA, dAu

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# Future Measurements: High Statistics Au+Au

- **Comparison of inclusive photon $v_2^{incl}$ from Au+Au at 200 GeV**
  - **Combined statistics 2007 & 2010 data**    *PHENIX: Phys. Rev. C 91 064904 (2015)*
  - **22% of 2014 data**
  - **2014 + 2016 Au+Au data more than 10x statistics compared to published results**

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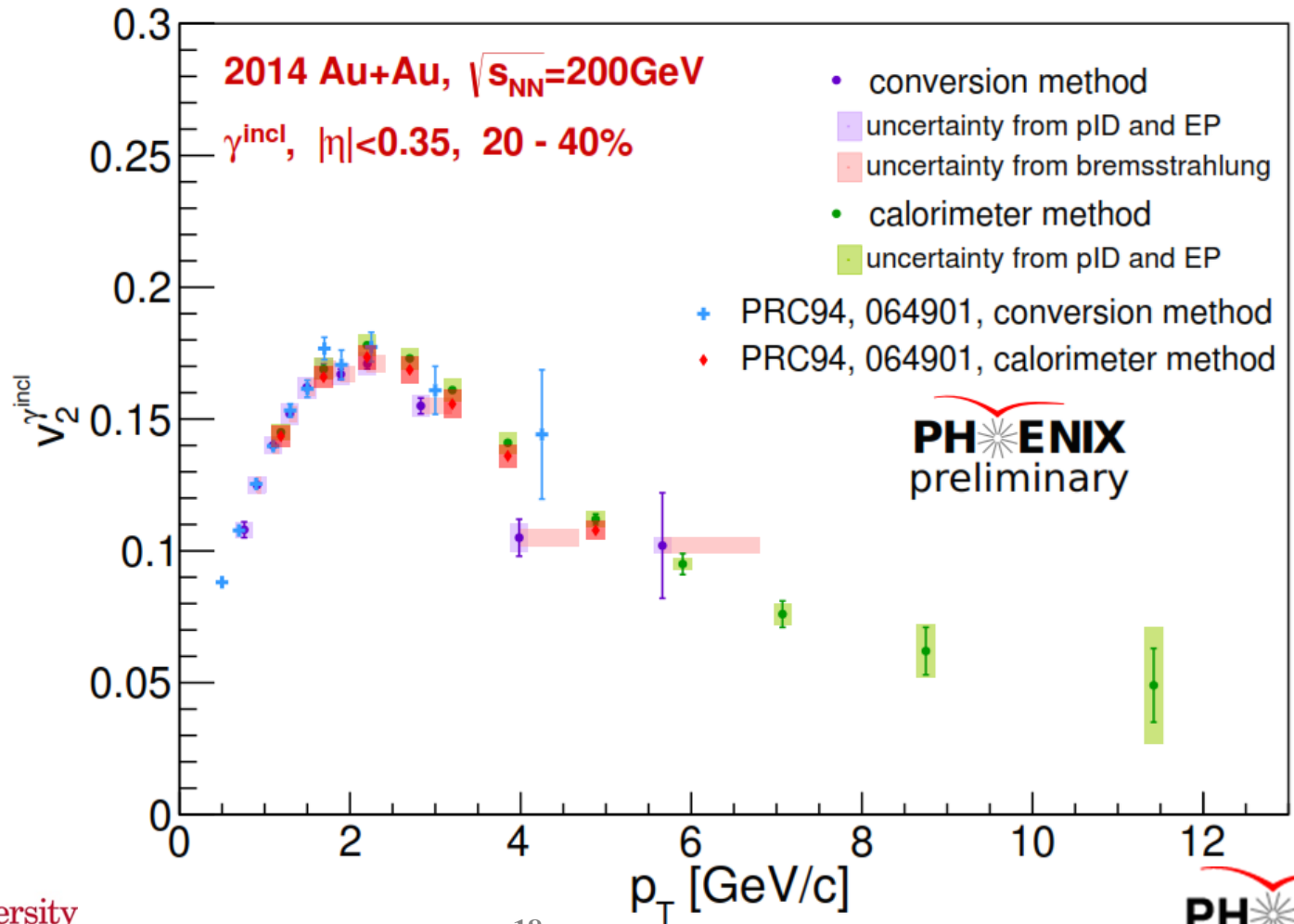
# Future Measurements: Different Systems

## $2.0 < p_T < 2.5$ GeV/c
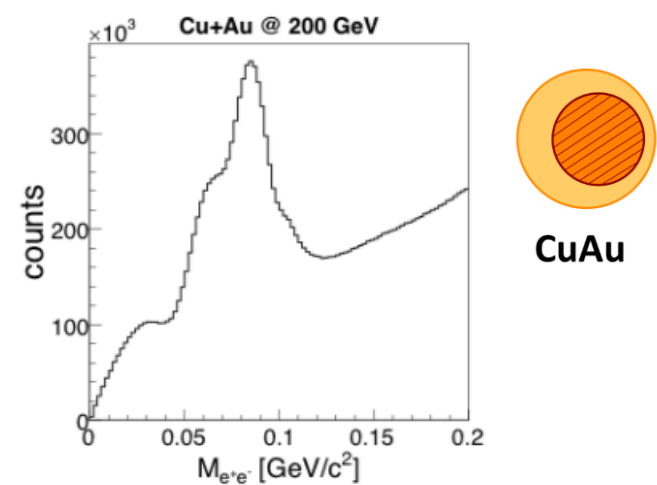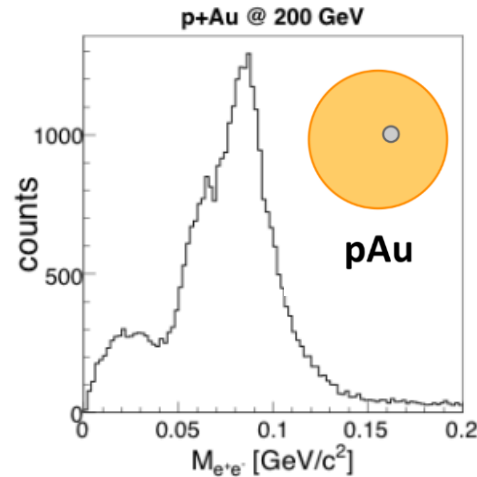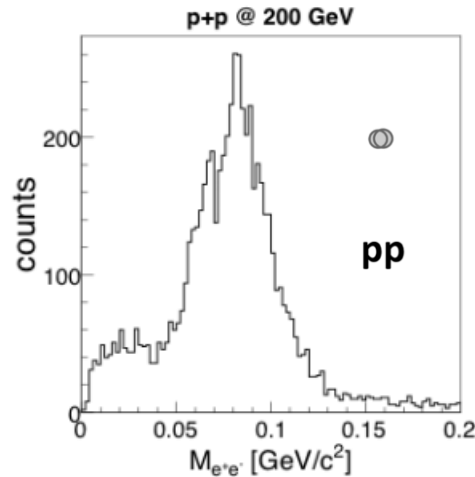


**Clear photon signal in all systems**

- **Data will provide interesting new information on:**
  - **Direct photon spectrum from p+p at low $p_T$**
  - **Search for thermal photons from small systems p+Au, d+Au and $^3$He+Au**
  - **Variation of collision geometry with Cu+Au to test origin of $v_2$**

# Summary and Outlook

- **Well established measurement of low momentum direct photon in Au+Au at 200 GeV from PHENIX**
  - Large yield above expected contribution from pQCD
  - Centrality dependence of yield $\sim N_{part}^{1.4}$
  - Large anisotropy $v_2$ with respect to reaction plan

- **Consistent data from LHC in Pb+Pb at 2.76 TeV**

- **Thermal photon puzzle persists**

- **New data from Cu+Cu at 200 GeV and Au+Au at 62.4 & 39 GeV**
  - Consistent with observed $\sim N_{part}^{1.4}$ dependence
  - Possible trend of inverse slope $T_{eff}$ with beam energy

- **More measurements to come in from future:**
  - High statistics Au+Au data (factor >10) from 2014 & 2016
  - Data from different collision geometry Cu+Au
  - Low momentum data from p+p (2015)
  - Search for direct photons in small systems p+Au (2015), d+Au (2016), 3He+Au (2014)

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# Thank you

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